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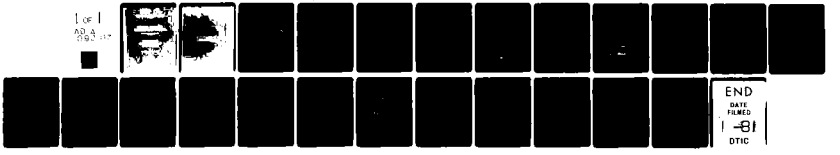

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TECHNICAL NOTE NO. 80-20

NEUTRON DOSIMETRY USING A TISSUE-EQUIVALENT IONIZATION CHAMBER

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ABSTRACT

A system for the measurement of neutron tissue dose or kerma has been assembled and tested. The dosimeter is a tissue-equivalent ionization chamber, of modified commercial design. It is enclosed in an airtight aluminum shell, which can be filled with tissue-equivalent gas and sealed, thereby eliminating the need for continuous gas flow. Ionization current can be measured using either a commercial electrometer or a DREO-constructed electrometer. The latter instrument enables the readout device to be located far from the dosimeter without an increase in the leakage current. Calibration theory and procedures are described, and correction factors discussed.

RÉSUMÉ

On a monté et vérifié un système de mesure d'où la dose ou le kerma tissulaire neutronique. Le dosimètre consiste en une chambre d'ionisation équivalent-tissu de modèle commercial modifié. Celle-ci est contenue dans une enveloppe en aluminium que l'on peut remplir d'un gaz équivalent-tissu puis que l'on peut fermer hermétiquement. De cette façon, il n'est pas nécessaire d'avoir un écoulement continu de gaz. On peut mesurer le courant d'ionisation à l'aide d'un électromètre commercial ou d'un électromètre fabriqué au CRD. Avec ce dernier, on peut placer le dispositif d'affichage des résultats loin du dosimètre sans qu'il n'y ait augmentation du courant de fuite. On décrit le principe et les méthodes d'étalonnage et on traite des facteurs de correction.

INTRODUCTION

One of the research objectives of the Protective Sciences Division of DREO is the prediction of the acute effects on man of exposure to neutron and gamma-ray radiation. A step towards the fulfilment of this objective was the recent initiation of a program to measure the relative biological effectiveness of neutrons for the production of certain physiological effects in small animals. This program resulted in a requirement for a device capable of accurately measuring neutron tissue kerma at high kerma rates (up to about 100 rads h^{-1}). Of the several devices available for neutron dosimetry, the most suitable one for radiobiology experiments is the tissue-equivalent (TE) ionization chamber.

A TE chamber is normally constructed with conducting, tissue-equivalent-plastic walls enclosing a cavity filled with a tissue-equivalent-gas mixture. It is a homogenous device to the extent that the atomic composition of the walls and the gas are the same and that phase effects can be neglected. It is tissue-equivalent to the extent that the atomic compositions of the walls and the gas duplicate the composition of standard muscle tissue. The more nearly homogeneous and tissue-equivalent a chamber is, the easier it is to calibrate accurately for measurement of tissue kerma in a neutron field.

The nature of the planned radiobiological experiments imposes additional constraints on the design of a suitable ionization chamber. For most ionization chambers currently used in neutron dosimetry, gas purity is ensured by maintaining a continuous flow of gas through the cavity. This requires that a tube connect the chamber to a large gas supply during measurement, and that flow rates be carefully regulated. The need for continuous gas flow can be overcome by enclosing the chamber in a thin, air-tight vessel which can be filled with gas to a specified pressure, then sealed and disconnected from the gas handling system. In addition to resulting in a more compact and portable dosimeter, this arrangement obviates the need for pressure and temperature corrections, since the mass of the gas in the cavity is constant.

The overall dimensions of the chamber are limited by the requirement that it fit into an animal holder, which is a tube 3.8 cm in diameter. At the same time, it is advantageous to keep the active volume as large as possible in order to maximize sensitivity. The wall thickness must be sufficient to ensure charged-particle equilibrium in the cavity, but not so great as to produce unwanted attenuation of the incident radiation.

An ionization chamber satisfying these conditions was constructed by Far West Technology, Incorporated, (FWT) of Golita, California. It is a substantially modified version of one of their standard line of tissue-equivalent ionization chambers. This Technical Note describes the chamber, its characteristics and calibration, and the ancillary equipment required to use it.

DESCRIPTION OF THE IONIZATION CHAMBER

The construction of the FWT TE ionization chamber is illustrated in figure 1. The active volume lies between the central electrode and the spherical outer electrode, both of which are constructed of A-150 type, conducting, tissue-equivalent plastic (1, Appendix C). There is a grounded guard ring (not shown in the figure) located between the electrodes and insulated from them; it helps to reduce leakage current and to define the active volume. High voltage is maintained between ground and the outer electrode, and ionization current is measured between ground and the inner electrode. The diameter of the cavity is 1.78 cm, which provides an active volume of nearly 3 cm^3. The wall thickness is 0.25 cm, sufficient to ensure charged particle equilibrium (CPE) within the cavity for the most energetic secondary protons produced by 15-MeV neutrons (1). The TE-plastic components are enclosed by a 0.025-cm-thick aluminum shell, in the shape of a right circular cylinder. The maximum outside diameter of the housing is 2.65 cm. An aluminum tube, 0.64 cm in diameter, connects the housing to a connector block, and provides a passage for TE gas and the signal and high-voltage wires. The connector block is machined from a solid piece of aluminum, and provides a sturdy clamping point. At the other end of the connector block are located a BNC signal connector, an MHV high voltage connector, and a Swagelok vacuum-tight quick-connect.

The volume enclosed by the aluminum shell and tubing is evacuated and filled with one atmosphere of gas using a gas handling system connected at the Swagelok quick-connect. (The gas handling system is described in the next section). The TE gas is a mixture of 55% propane, 39.6% carbon dioxide, and 5.4% nitrogen (per cent partial pressure). Its atomic composition is compared with that of A-150 TE-plastic and ICRU standard muscle tissue (1) in Table 1. Also shown in the table is the composition of a methane-based TE-gas mixture which is in common use.

Preliminary tests of the ionization chamber revealed that a large component of the measured ionization current was being produced inside the connector block. When the block was opened, it was found that bare high voltage and signal wires were located only about 1 cm apart in the air-filled cavity. The connector block was therefore behaving as a second active volume. The problem was corrected by inserting a piece of Teflon between the wires, and filling the rest of the cavity with ground Teflon. (Teflon was used to avoid the production of recoil protons in a neutron field). This modification reduced the unwanted current to a negligible level.

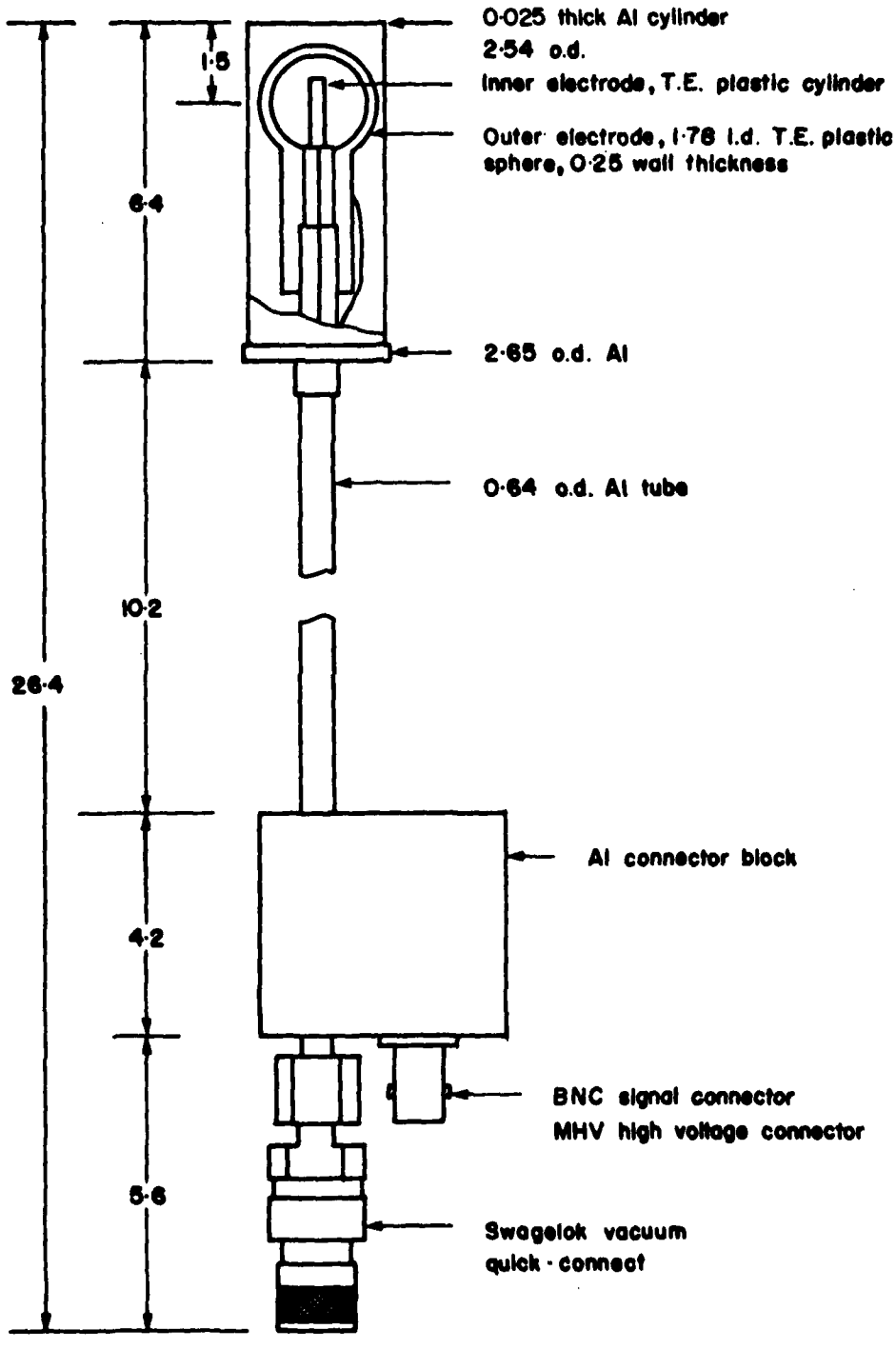

Figure 1. Construction of the FWT tissue-equivalent ionization chamber. All dimensions are in cm.

Table 1.

Elemental Composition of Tissue-like Materials

Material	Percent Elemental Weights				
	H	C	N	O	Others
ICRU muscle tissue	10.2	12.3	3.5	72.9	1.1 Na + Mg + P + S + K + Ca
A-150 muscle tissue-equivalent plastic	10.1	77.6	3.5	5.2	1.8 Ca, 1.7 F
TE gas mixture, with propane	10.3	56.9	3.5	29.3	
TE gas mixture, with methane	10.2	45.6	3.5	40.7	

GAS-FILLING SYSTEM

In order to ensure high purity of the TE gas in the ionization chamber, it is necessary to periodically evacuate the chamber and refill it. It is desirable to have accurate control of the fill pressure so that the chamber does not need to be recalibrated after each filling (assuming that the temperature is the same at each filling).

The gas handling system used to fill the ionization chamber is illustrated in figure 2. A gas manifold, constructed by Far West Technology, is used to connect the chamber either to a mechanical vacuum pump or to a cylinder of compressed TE gas. The manifold is equipped with an aneroid vacuum gauge, but since it is intended for use with a low-pressure proportional counter, it has a range of only 0-200 mm Hg. The fill pressure is therefore measured using a mercury manometer made by Sargent-Welch. Although the manometer is intended for use as a closed-end device with an absolute pressure range of 0-760 mm Hg, in practice it was found to be readable only over the range 0-700 mm Hg. It is therefore used as a differential gauge with one arm open to the atmosphere. Absolute pressure is determined by reading atmospheric pressure from a nearby mercury barometer, and adding the result to the differential pressure indicated by the manometer.

The manometer is connected to the rest of the system via a trap containing cleaned copper turnings. The purpose of the trap is to prevent mercury vapour from dissolving in the brass components of the valves and connectors. When most of the copper turnings have changed colour, indicating they are saturated with mercury, it is necessary to replace them. The fresh turnings should be carefully degreased using trichlorethylene before being put into use.

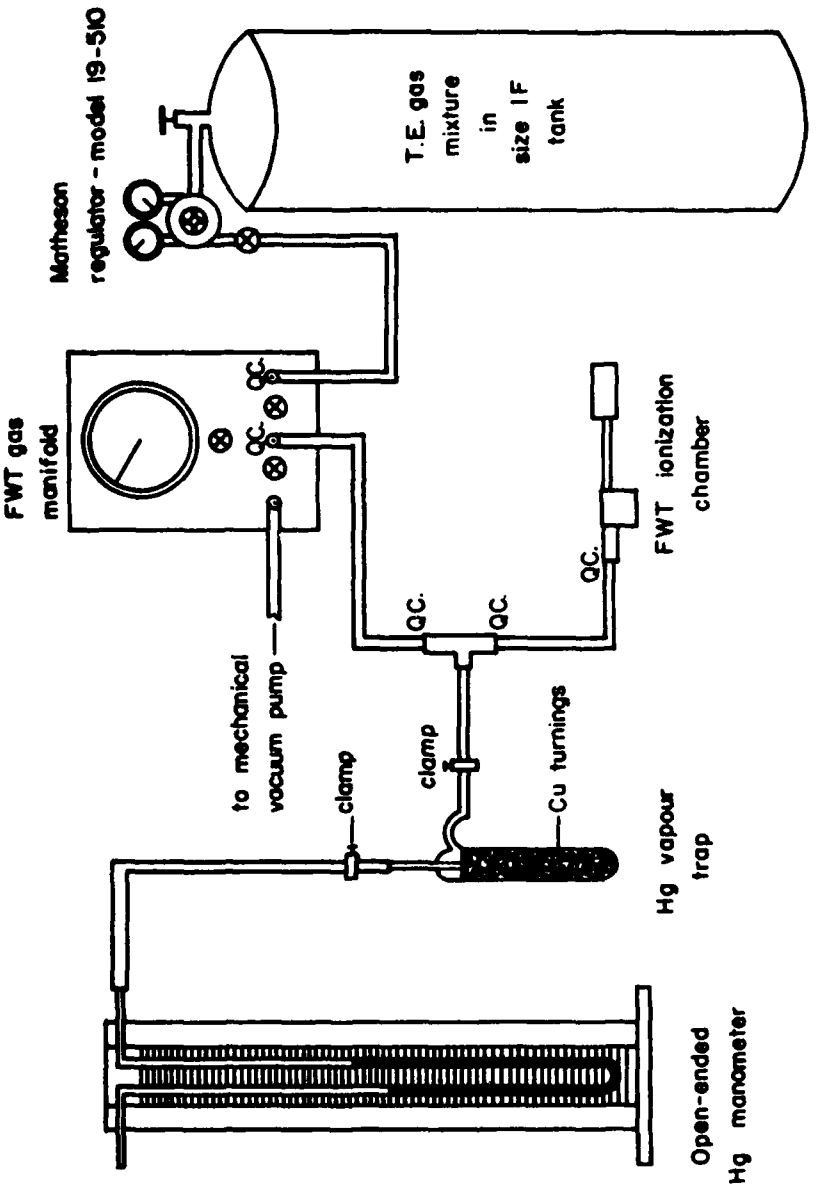

Figure 2. Gas handling system for evacuating and filling the ionization chamber. Connections marked "Q.C." are Swagelok quick-connects.

The usual procedure for refilling the ionization chamber is as follows:

1. All the quick-connect connections (indicated in the figure by "Q.C.") are made, except the one for the chamber itself.

2. The lines and gauges are evacuated; a vacuum has been reached when the mercury columns in the manometer stop moving. At this point, the difference in height of the mercury columns should give the same value of atmospheric pressure as the barometer, indicating no serious leaks in the system.

3. The lines and gauges are filled to about one atmosphere with TE gas, indicated by the mercury columns being at the same height.

4. The ionization chamber is connected; it is assumed to have been previously filled to one atmosphere pressure with TE gas.

5. The system is again evacuated, refilled to about one atmosphere, and evacuated again. This flushing procedure helps to ensure that all impurities are removed from the chamber.

6. Finally, the chamber is filled to 760 mm Hg pressure, using the manometer to correct for the difference between standard pressure and the current atmospheric pressure. The chamber is then disconnected by pulling apart the quick-connect in a smooth but rapid motion. The rest of the system should be left full of TE gas to help prevent contamination.

There are some other points which should be noted:

1. When not in use, the copper-filled mercury trap should be isolated by closing clamps on the tubing on either side of it. This will prolong the useful lifetime of the copper turnings.

2. The valve which isolates the aneroid pressure gauge leaks slightly so it should be left open throughout the entire filling procedure to ensure that pressure equilibrium can be reached. Although the upper limit on the scale of this gauge is 200 mm Hg, the mechanism will not be damaged by absolute pressures up to about 950 mm Hg.

3. When refilling is complete and the vacuum pump turned off, it should be disconnected to prevent pump oil from being sucked into the manifold.

Using the outlined procedure and observing the suggested precautions, it is possible to fill the chamber with clean TE gas to a pressure of 760 mm Hg with an accuracy of about ± 1 mm Hg. This represents a possible error of ± 0.13%, which is well within required limits.

CURRENT OR CHARGE MEASUREMENT AND TEST OF CHAMBER

The ionization current produced by a 3-cm^3 ionization chamber exposed to fields typical of radiobiological experiments is only of the order of 10^{-11} A. It is therefore necessary to measure this current (or the integral quantity, charge) with a very sensitive and precise instrument.

An instrument suitable for most applications is the Keithley Model 616 Digital Electrometer. It can be used to measure current as low as 10^{-15} A, or charge as low as 10^{-14} C. Its absolute accuracy in the lowest ranges is specified to be ± (5% of reading + 0.1% of range), but its relative accuracy or precision has been observed to be better than 1%. Since it is the combination of chamber and electrometer which is calibrated in a known radiation field, the relative accuracy is the appropriate figure of merit.

Leakage current is the component of the measured current due to sources other than ionization in the active volume of the chamber. Connecting the FWT chamber to the Keithley electrometer by a short length of ordinary coaxial cable, and applying a bias of ± 250 V, results in a current of about 2×10^{-15} A in the absence of ionizing radiation. This current is very sensitive to motion of the cable, so a low-noise type of cable is used. Low-noise coaxial cable has a graphite coating on the layer of insulation between the wire and the braid. The coating helps to prevent static charge buildup, which results from cable motion or flexion, and which contributes to the leakage current.

Tests were carried out to determine the effects of ion recombination and bias polarity on the ionization current. The chamber was placed in a 1000-R/h field of ^{60}Co gamma-radiation, and a bias voltage applied using an Ortec model-428 power supply. The voltage was varied from + 500 to + 100 V and from - 500 to - 100 V, and the current measured at each voltage after equilibrium had been reached. Figure 3 shows the results, plotted as $1/I$ versus $1/V^2$, as recommended by FWT. The data for each bias polarity are fitted to a straight line, which is extrapolated to $V = \pm \infty$ $(1/V^2 = 0)$. The value of the current at this voltage is the saturation current, corresponding to complete ion collection. The difference in the saturation currents for the two polarities is less than 0.5%, and the currents at bias voltage of ± 250 V are > 99% of the saturation current. Thus, in gamma-ray fields, 250 V is an adequate bias voltage, and the polarity effect is insignificant. However, in neutron fields a different type of recombination effect becomes important, and further tests for saturation should be made for each neutron energy spectrum and kerma rate used.

A check was also made of the effect of the orientation of the chamber relative to the incident radiation. The chamber was exposed end-on and side-on to ^{60}Co gamma-rays at exposure rates of 100 and 1000 R/h. The ionization currents were the same, within experimental errors, for both orientations at each exposure rate. It is clear that the response of the chamber cannot be completely isotropic, because of the presence of the stem. Since the stem and connector block subtend a small solid angle, however, the response will be nearly isotropic over a wide angular range.

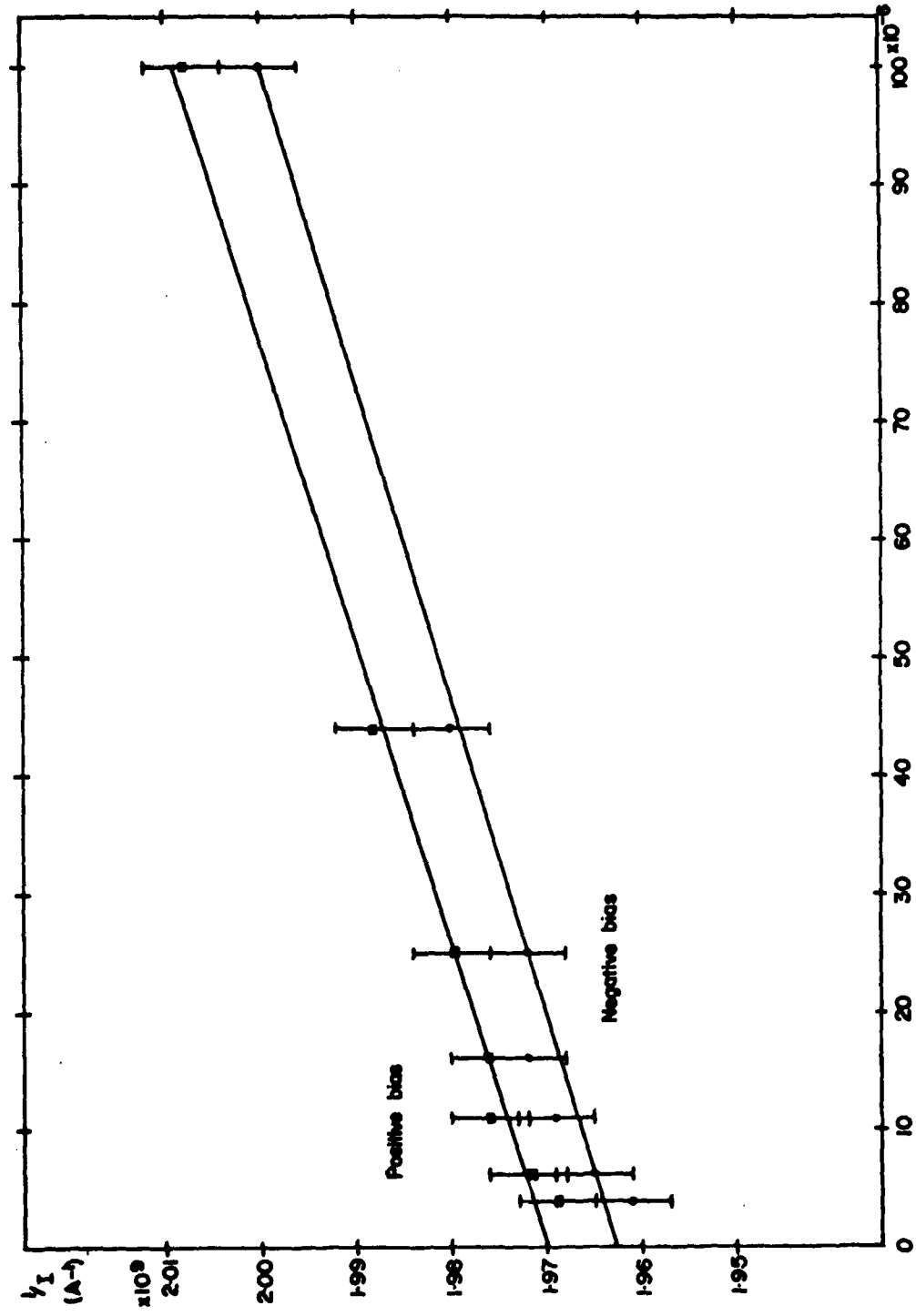

Figure 3. Saturation characteristics of the FWT ionization chamber for exposure to 1000R/h of ^{60}Co gamma-radiation. Error bars indicate relative errors. The straight lines result from least-squares fits of the data.

CALIBRATION OF THE IONIZATION CHAMBER

GENERAL THEORY

In this section, general equations for the calibration of an ionization chamber are derived. The nomenclature and some of the derivation follows Reference 1.

The total response of any type of dosimeter exposed to a mixed field of neutrons and gamma rays is given by

$$R_T = D_N/\alpha_N + D_G/\alpha_G, \tag{1}$$

where D_N and D_G are the absorbed tissue doses due to the two components of the field, and α_N and α_G are the response functions of the dosimeter for neutrons and gamma-rays. Similarly, the response of the dosimeter to a dose D_c of radiation in a calibration field is

$$R_c = D_c/\alpha_c. \tag{2}$$

Dividing Eq. (1) by Eq. (2) gives

$$R_T/R_c = (\alpha_c/\alpha_N)\ (D_N/D_c) + (\alpha_c/\alpha_G)\ (D_G/D_c). \tag{3}$$

In the particular case of an ionization chamber, whose response may be given as, e.g., ionization charge per unit mass of gas, relative sensitivities can be defined by

$$k_T = (\alpha_c/\alpha_N) = (\bar{W}_c/\bar{W}_N) \left[(s_{m,g})_c/(s_{m,g})_N \right] \left[(K_t/K_m)_c/(K_t/K_m)_N \right] \tag{4}$$

for neutron sensitivity relative to calibration sensitivity, and

$$h_T = (\alpha_c/\alpha_G) = (\bar{W}_c/\bar{W}_G) \left[(s_{m,g})_c/(s_{m,g})_G \right] \left[(K_t/K_m)_c/(K_t/K_m)_G \right] \tag{5}$$

for gamma-ray sensitivity relative to calibration sensitivity. The parameter $\bar{W}$ is the mean energy deposited in the chamber gas per ion pair produced, $s_{m,g}$ is the ratio of effective mass stopping power for the charged secondary particles in the wall material to that in the gas, and K_t/K_m is the ratio of kerma in tissue to kerma in the wall material.

Equation (3) can be rewritten

$$R_T/R_c = k_T(D_N/D_c) + h_T(D_G/D_c)\ , \tag{6}$$

or

$$R_T' = \alpha_c R_T = k_T D_N + h_T D_G\ ,$$

where R_T' is the "reduced" response, and has the same units as dose.

For exposure to a pure neutron field, the neutron tissue dose is given by

$$D_N = (\alpha_c/k_T)\, R_T$$
$$= (\bar{W}_N/\bar{W}_c) \left((s_{m,g})_N/(s_{m,g})_c \right) \left((K_t/K_m)_N/(K_t/K_m)_c \right) \alpha_c R_T \qquad (7)$$

This last expression also gives a good approximation to the total dose in a mixed field, provided that $h_T \approx k_T$, and $D_G << D_N$. If these conditions do not obtain, it is necessary to use a second ionization chamber having much different values of k and h; usually a neutron-insensitive chamber or a Geiger-Müller counter is used. The neutron and gamma-ray doses can then be derived from the responses of the two chambers.

In general, the values of the parameters W, s, and K in Eq. (7) are not accurately known. They depend upon the energy spectrum of the neutrons, which is not usually directly measured. They are also based upon experimental data which may have large uncertainties. If the chamber could be calibrated in a neutron field with a similar energy spectrum to that of the neutron field to be measured, the three ratios in Eq. (7) would all be very close to unity, and uncertainties in the parameters would be unimportant. Calibrated fast-neutron sources are not generally available, however, so the usual practice is to calibrate the chamber in the gamma-ray field of a ^{60}Co or ^{137}Cs source.

The ionization chamber is positioned in the calibration gamma-ray field, and the ionization charge Q (or current I) is measured for a given exposure X (or exposure rate $\dot{X}$). The calibration coefficient is given by

$$N_c = X/Q \ (= \dot{X}/I), \qquad (8)$$

where Q (or I) is assumed to have been corrected for various effects peculiar to the design of the chamber, such as attenuation and scattering in the walls, incomplete ion collection, and geometrical effects. Exposure can be converted to tissue dose using a standard factor:

$$D_c = f_{t,c} X$$
$$= (\bar{W}_{air,c}/e) \left((\mu_{en}/\rho)_{t,c}/(\mu_{en}/\rho)_{air,c} \right) N_c Q = \alpha_c Q \qquad (9)$$

where e is electronic charge, μ_{en}/ρ is the mass energy absorption coefficient, and the meaning of the subscripts is obvious. Putting the expression for α_c implied in Eq. (9) into Eq. (7) gives for the neutron tissue dose:

$$D_N = (\bar{W}_N/\bar{W}_c) \left((s_{m,g})_N/(s_{m,g})_c \right) \left((K_t/K_m)_N/(K_t/K_m)_c \right)$$
$$\times (\bar{W}_{air,c}/e) \left((\mu_{en}/\rho)_{t,c}/(\mu_{en}/\rho)_{air,c} \right) N_c Q. \qquad (10)$$

Under conditions of charged particle equilibrium,

$$(K_t/K_m)_c = (\mu_{en}/\rho)_{t,c}/(\mu_{en}/\rho)_{m,c} ,$$

so Eq. (10) becomes

$$D_N = (\bar{W}_n/\bar{W}_c) \left\{ (s_{m,g})_N/(s_{m,g})_c \right\} (K_t/K_m)_N f_{m,c} N_c Q , \quad (11)$$

where

$$f_{m,c} = (\bar{W}_{air,c}/e) \left\{ (\mu_{en}/\rho)_{m,c}/(\mu_{en}/\rho)_{air,c} \right\} .$$

Again, the value of Q measured in the neutron field is assumed to be corrected for wall effects, etc.

An assumption implicit in the preceding derivation (beginning with Eqs. (4) and (5)) is that the cavity is small relative to the range in it of secondary charged particles originating in the wall material. While this is generally true for electrons resulting from gamma-ray irradiation, it does not hold for heavy charged particles resulting from neutron interactions in the walls of a chamber of practical size. In the case of a homogeneous chamber, however, the assumption is not required. The result expressed in Eq. (11) is therefore correct to the extent that the chamber can be considered homogeneous (and consequently $s_{m,g} = 1$). For inhomogeneous chambers, an accurate derivation requires that the relative contributions of wall- and gas-produced ions to the total ionization be taken into account (2,3,4).

FWT IONIZATION CHAMBER CALIBRATION

The main calibration source at DREO is a 530-curie ^{60}Co source, which emits gamma rays with a mean energy of 1.25 MeV. A thickness of 0.5 cm of unit-density tissue-equivalent material is ideally required to ensure electronic equilibrium for this radiation, but in practice 0.4 cm has been found to be sufficient (5). Since the density of A-150 TE plastic is 1.12 mg/cm^3 (6), a flat thickness of about 0.36 cm would be required to produce charged particle equilibrium. The spherical wall of the FWT ionization chamber is 0.254-cm thick (plus the 0.025-cm-thick aluminum shell and a thin layer of TE gas); consequently true CPE is not achieved for radiation normally incident on it. However, the mean effective wall thickness, averaged over the cross-section of the cavity, is 0.35 cm, so a condition of CPE very nearly exists for ^{60}Co gamma rays. It will be assumed that CPE does apply;the error introduced is expected to be less than 1%. This assumption would not be required if a ^{137}Cs source were used for the calibration, since the 0.66 MeV gamma rays produced by this isotope only require a thickness of about 1.5 mm of TE material for CPE. It is recommended that if an accurately calibrated ^{137}Cs source of sufficient activity becomes available, it should be used to calibrate the chamber.

The effect of radiation attenuation and scattering in the wall of an ionization chamber is usually measured by adding layers of wall material to the chamber. Ionization charge is then plotted as a function of wall thickness, and the data are extrapolated to zero thickness. The ratio of the charge at zero thickness to that at the thickness used for a measurement is the correction factor for wall effects. This procedure is not possible with the FWT ionization chamber because of its aluminum shell. Wall effects have therefore been estimated from other researchers' published data. For 2-MV X-rays incident on a TE chamber with a wall thickness of 520 mg cm^{-1}, Williams and Greening (7) quote an attenuation correction factor of 1.013. The correction required for ^{60}Co gamma-rays incident on the FWT chamber, whose wall is about 280 mg cm^{-2} thick, would be less than 1%, and will be neglected.

The ionization chamber was exposed to ^{60}Co gamma-radiation at exposure rates of 100-300 R/h, which is approximately the range for which the field had been accurately calibrated. On the basis of several trials, the calibration coefficient was found to be $N_c = 5.40\ (\pm\ .02) \times 10^8$ R/C, when the chamber has been recently filled with 760 mm Hg-pressure of propane-based TE gas at a temperature of about 20°C. The value of the coefficient decreases with time after filling, a result of gas exchange with the TE plastic. Soon after the chamber was received, the rate of change was about 0.1% per day. The rate has since decreased, and is expected to continue to decrease as the chamber ages. The chamber should be kept filled with the same type of TE gas at all times to avoid disturbing the equilibrium between the gas and the plastic.

To use the ionization chamber in a neutron field, the calibration coefficient must be modified by the other factors indicated in Eq. (11). Since accurate values are not available for most of these factors, some assumptions and approximations must be made. The first assumption is that the chamber is homogeneous, so that $(s_{m,g})_N = (s_{m,g})_c = 1$. Coppola and Porro (8) quote a value of $s_{m,g} = 1.006$ for 0.661-MeV gamma rays, so the approximation $(s_{m,g})_c = 1.0$ is a good one. Several authors (3,4,8) have presented calculated values of $s_{m,g}$ for neutrons of energies from 0.57 to 15 MeV, for chambers with A-150-plastic walls filled with methane-based TE gas. There is little consistency among these authors, but all of them give $(s_{m,g})_N = 1.00 \pm .03$ for all neutron energies. Since propane-based TE gas is even closer in atomic composition to A-150-plastic than the methane mixture (Table 1), it seems reasonable to set $(s_{m,g})_N = 1.0$ also. The values of $s_{m,g}$ quoted so far neglect the possibility of any phase effects. Thwaites and Watt (9) have calculated the stopping power ratio $(S/\rho)_{gas}/(S/\rho)_{solid}$ for tissue-like materials described by the formula $C_5H_{40}O_{18}N$. They find a maximum value of 1.08 at a neutron energy of 150 keV, decreasing to about 1.05 at 1 MeV and 1.02 at 8 MeV. These values have large uncertainties, but they do seem to indicate a definite phase effect. Until more accurate results become available, however, the effect will be neglected.

There is also considerable uncertainty in the value of the ratio $(\bar{W}_N/\bar{W}_c)$. In reference 1, it is recommended that the value 1.05 be used, with an uncertainty of about 5% for neutron energies above 1 MeV, and a greater uncertainty at lower energies. This value is based on studies using methane-based TE gas, which has a significantly different value of $\bar{W}_N$ from the propane-based gas used here. The ratio, however, should be very similar for the two gas mixtures, and so the value 1.05 will be adopted for this work.

Recent experimental values for the factor $f_{m,c}$ are available for several gamma-ray energies (7). The value determined for ^{60}Co gamma-radiation is 0.952 rad R^{-1}; no uncertainty is specified, but it is unlikely to be greater than 0.5%.

Finally, the kerma ratio depends upon the neutron energy spectrum. For a given spectrum, it can be calculated using the kerma factors in Appendix A of Reference 1. Examples of $(K_t/K_m)_N$ are 1.05 for 1-MeV neutrons, and 0.96 for 14-MeV neutrons.

The expression relating charge in coulombs to neutron dose in tissue rads, for a ^{60}Co calibration, is thus

$$D_N = 5.40 \times 10^8 \, (K_t/K_m)_N \, Q. \qquad (12)$$

Radiation fields are more appropriately specified in terms of tissue kerma (or kerma rate) in air. Since CPE exists in the FWT ionization chamber for all neutron spectra to which it will be exposed, and since Q is assumed to have been corrected for wall effects, tissue kerma is equal to the dose given by Eq. (12). (The relationship between dose and kerma is discussed in detail in Reference 1.)

Attenuation and scattering in the chamber walls are more important for neutrons than for ^{60}Co gamma-rays. Meier and Burger (10) have measured wall effects for a spherical TE chamber with a volume of 1 cm^3, using the technique outlined earlier. They plot $\log(Q/Q_o)$ versus mean wall thickness. for neutron energies 15, 5.5, 2.1, and 0.67 MeV. From their graph, values of Q_o/Q (the correction factor) can be estimated for the FWT chamber, based on a mean wall thickness of 3.6 mm. The results are:

E (MeV):	15	5.5	2.1	0.67
Q_o/Q :	1.003	1.014	1.028	1.077

Corrections are small at high neutron energies (>10 MeV), but become large at low energies (< 1 MeV). The factors at energies other than those listed may be approximated by interpolation on a graph of Q_o/Q versus $\log(E_N)$.

DESIGN OF THE DREO ELECTROMETER

Although the Keithley 616 electrometer is a very satisfactory instrument for the measurement of ionization current, it is extremely sensitive to radiation and must be well shielded from intense fields. For the tests performed at DREO, a seven-metre-long low-noise cable was sufficient to allow the electrometer to be located at a position of low radiation intensity. At some of the proposed locations for radiobiology experiments, a much longer cable, exposed to more intense radiation, would be needed, Even a low noise cable, under such conditions, may be expected to produce a significant leakage current. In order to avoid this potential source of error, an alternative electrometer has been designed and built at DREO. It employs a radiation-insensitive electrometer head which is connected directly to the connector block of the FWT ionization chamber, thereby avoiding the need for lengthy cables carrying very small currents.

The complete circuit diagram of the DREO electrometer is shown in Figure 4. The components making up the small electrometer head are enclosed by the dashed line, and the remaining components are housed in a single-width NIM module. The ionization current from the chamber is detected at the high-impedance input of the source follower Q1, which charges capacitor C1 through the open-loop amplifier A1. When the voltage across C1 reaches a level predetermined by the setting of R11, the discriminator A2 produces a pulse which passes through the inverter/buffer A4, the diode D3 and the emitter follower Q3, and then on to an external counter (any NIM standard) via a BNC cable. The output pulse from A2 also turns on FET Q2 which in turn discharges C1. As long as switch S1 is on, the electrometer continues to recharge C1, and each pulse produced represents an equal amount of ionization charge. NOTE: the design of the circuit requires that the high-voltage bias on the chamber be of negative polarity.

When S1 is off, the negative voltage passed by buffer A3 and diode D2 holds Q2 on and effectively short-circuits C1;the electrometer is thus disabled. The LED D4 provides visible confirmation that the electrometer is enabled.

The resistor R1 and the ±12-volt potential (supplied by the NIM power supply) provide a constant-current source for Q1, which must have a gain of unity or less to prevent A1 latch-up (a condition which would prevent A1 from charging C1). The low offset current and voltage, and the low input bias current of a model-LM308A amplifier make it a good choice for A1. A model-741 amplifier is adequate for A3, but the faster model 709 is required for A2 and A4.

The switch Q2 must have low leakage current to prevent the unwanted discharge of C1 while Q2 is off. A MOS-FET device was used for this reason. The low leakage requirement extends also to the integrating capacitor C1, and dictates that a silver-mica or Mylar capacitor be used.

The very small input currents and high levels of exposure to both gamma-rays and neutrons place severe constraints on the construction of the electrometer head. A Teflon sleeve is used to insert the J-FET Q1 into a brass guard ring. Pin 7 of Q1 is connected to the ring, which in turn is grounded

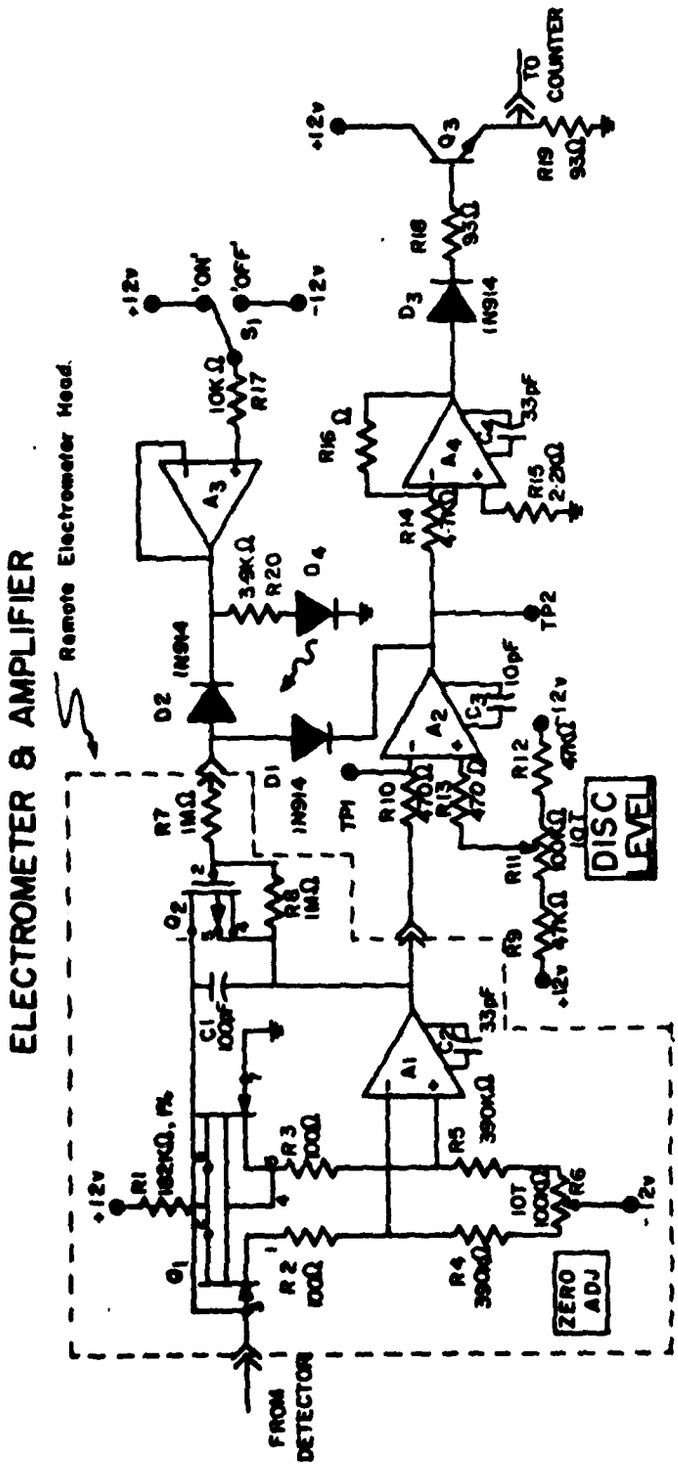

Figure 4. Circuit diagram for the DREO electrometer.

to the electrometer case. The sleeve/Q1/brass ring combination is fitted into a Teflon block, which fills a large proportion of the case volume to reduce the possibility of spurious currents being produced. All surfaces of the block are coated with a conductive colloidal dispersion of graphite, and the block is then bolted to the electrometer case, thus providing a guarded signal path to Q1. To minimize pick-up and stray capacitance, the Q1-C1 connection was made as short as possible. Leakage currents were also kept to a minimum by removing all dirt, grease, resin, etc., from the leads and cases of Q1 and C1.

The connection between the ionization chamber and the electrometer head is made using a rigid BNC adaptor. The electrometer head is connected to the NIM part of the circuit by a thin, seven-conductor cable, and the connections are made at both ends with Bendix ten-pin connectors.

Tests were conducted with the ionization chamber located in a ^{60}Co gamma-ray field. Leakage current attributable to the electrometer was found to be insignificant. Response was linear to within 1% over the exposure-rate range 100-1000 R/h. The minimum exposure for which the maximum count error is 1% (corresponding to 100 counts) is about 4 R. A lower value of C1 produces shorter ramp times (more pulses per unit exposure), reducing this lower limit, but also resulting in a significant non-linearity of reponse at high exposure rates. The value chosen, 100 pF, is thus a compromise appropriate for the exposure-rate range of interest.

The calibration procedure is parallel to that used with the Keithley electrometer as a current-measuring device, except that the response is measured in counts (or count rate) rather than coulombs (or amperes). Calibration measurements over the exposure-rate range 100-300 R/h yielded a coefficient $N = 3.84\ (\pm\ .02) \times 10^{-2}$ R/count. The conversion for use in a neutron field is again given by Eq. (11), which with the appropriate parameters put in becomes

$$D_N = 3.84 \times 10^{-2}\ (K_t/K_m)_N P,$$

where P is the number of counts.

CONCLUSION

A system for measurement of neutron tissue kerma and kerma rates has been established. It is based on a tissue-equivalent ionization chamber of custom design. It is capable of measuring kerma rates as low as 0.5 rad h^{-1} using a Keithley electrometer, or of measuring kerma as low as about 4 rads using an electrometer built at DREO. The latter device also permits the use of the chamber at locations remote from a readout device, without the high leakage current which would normally result from a long cable. The response of the chamber to ^{60}Co gamma-radiation is linear to at least 1000 R h^{-1}, and is isotropic over at least 2π steradians.

A continuous flow of TE gas to the ionization chamber is not required, eliminating the need for cumbersome gas supplies and flow regulators. The chamber is well suited for short-term use at other laboratories, since it need only be refilled at DREO at intervals of two weeks or more.

The absolute accuracy of the dosimeter's calibration, assuming calibration in a gamma-ray field, is estimated to be 10%, and is limited primarily by uncertainty in the parameters which are used to calculate the conversion factor for use in a neutron field. Relative accuracy is expected to be about 5% for measurement in different neutron fields, and 2% for different measurements in the same field.

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A system for the measurement of neutron tissue dose or kerma has been assembled and tested. The dosimeter is a tissue-equivalent ionization chamber, of modified commercial design. It is enclosed in an airtight aluminum shell, which can be filled with tissue-equivalent gas and sealed, thereby eliminating the need for continuous gas flow. Ionization current can be measured using either a commercial electrometer or a DREO-constructed electrometer. The latter instrument enables the readout device to be located far from the dosimeter without an increase in the leakage current. Calibration theory and procedures are described, and correction factors discussed

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